Improved Drying and Storage Practices that Reduce Aflatoxins in Stored Maize: Experimental Evidence from Smallholders in Senegal

Jonathan Bauchet, Stacy Prieto, and Jacob Ricker-Gilbert

Proper post-harvest treatment of crops is key to limiting contamination by aflatoxins, potent carcinogens, but little is known about constraints to adoption of best post-harvest practices among smallholder farmers in developing countries. We use a randomized controlled trial with 2,000 maize producers in Senegal to test whether low awareness and/or lack of drying and storage technologies are barriers to storing safe maize. A novel feature of our intervention is that we offered both drying and storage technologies to farmers and evaluated their combined impact. We found that only hermetic (airtight) storage bags caused a statistically significant reduction in total aflatoxin levels after 3–4 months of storage, reducing the likelihood that maize had total aflatoxin levels above safe-to-eat thresholds by 30%. Our results provide practical guidance to lower aflatoxins in staple crops and suggest that strategies to reduce aflatoxins should address issues from harvest to storage in a comprehensive manner.

Key words: Aflatoxins, grain drying, hermetic bag, improved storage technology, PICS, post-harvest practices, Senegal, sub-Saharan Africa.

JEL codes: I15, I31, O13, O31, Q12.

As many smallholder farmers in the developing world consume much of what they produce, deficient on-farm food safety practices are likely to be a major contributor to the poor health of millions of people. One critical food safety problem is exposure to aflatoxins, toxic compounds produced by certain fungal species of the *Aspergillus* family that are frequent contaminants of maize, groundnuts, and other agricultural products. Aflatoxins are invisible, odorless, and tasteless, making them particularly difficult to control (Lewis 2004; NTP [National Toxicology Program] 2016, 2019). This is a major health challenge, as an estimated 4.5 billion people in the developing world are chronically exposed to aflatoxins (*Williams et al.* 2004). The World Health Organization estimates that 20,000 deaths occurred from aflatoxins in 2010, with over 600,000 years of life lost (Havelaar et al. 2015). An estimated 28% of liver cancers worldwide, and up to 40% in Africa, are attributable to exposure to aflatoxins (Liu and Wu 2010). Other negative health effects likely include growth impairment, neural tube defects, and immune suppression in both children and adults (Shephard 2008; Wild and Gong 2010). In turn, poor health reduces economic growth in developing countries (Bhargava et al. 2001; Bloom, Canning, and Sevilla 2004; Weil 2007).

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Correspondence to be sent to: jrickerg@purdue.edu

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This article reports findings from a randomized controlled trial (RCT) that measures which constraint(s) prevent smallholder farm households from improving the safety of their own food production. We provided the treated households in southern Senegal with training on proper post-harvest practices and with three inputs aimed to improve drying and storage of maize, the main food crop. The treatments offered in our intervention are designed to test the most important constraint(s) to addressing aflatoxin contamination among smallholder farm households in sub-Saharan Africa (SSA). For example, training potentially corrects for smallholders' lack of knowledge of aflatoxins and other food safety hazards (Udomkun et al. 2017). In addition, the inputs – moisture meter, tarp, and hermetic (airtight) grain storage bag – are simple technological innovations with the potential to improve the safety of stored maize but that have yet to be tested for prevention of aflatoxins in staple foods on a large scale. Providing tarps tests whether lack of sufficient technologies to thoroughly and cleanly dry staple grains is a significant constraint to reducing aflatoxins, while the moisture meter tests if lack of an accurate moisture determination method is a key constraint. Finally, receiving the hermetic bag tests if lack of appropriate storage solutions that maintain foods safely during storage is an important constraint to reducing aflatoxin contamination in stored maize. (See Affognon et al. [2015] for a general review of post-harvest issues in SSA.)

Households living in villages assigned to the control group (group 1) received no input for the duration of the study. Households in the training-only group (group 2) were trained by local extension agents on the risks from aflatoxins and improved drying and storage practices but receive no inputs. Households in the hygrometer group (group 3) were trained and received a low-cost moisture detection device to determine when maize is dry enough for safe storage. Households in the tarp group (group 4) were trained, received a hygrometer, and received a 5×2 m (10 m^2) tarp as an alternative to drying maize on the bare ground. Finally, households in group 5 received training, a hygrometer, a tarp, and one 50-kg Purdue Improved Crop Storage (PICS) hermetic grain storage bag. PICS bags are designed for optimal chemical-free storage of crops but also control aflatoxins in two ways that we describe below.

The existing evidence on the effectiveness of interventions to reduce aflatoxins in staple crops in developing countries is very limited. To our knowledge, there are only two experimental studies that tested the effectiveness of interventions to reduce aflatoxins. First, a recent RCT by Hoffmann et al. (2018) to estimate the effect of providing Ghanaian smallholders with a plastic tarp for drying groundnuts; they found that tarp provision led to a 31% reduction in total aflatoxin levels. (Total aflatoxin refers to the sum of the four principle types of aflatoxins: B1, B2, G1, and G2.) Second, a recent study by Pretari, Hoffmann, and Tian (2019) used an RCT to test a set of aflatoxin-reducing post-harvest treatments in Kenya including training, tarps, hermetic bags, and an option to pay for a mobile drying service. The study reported that the training and tarps were most effective interventions at reducing aflatoxin levels in maize, doing so by over 50%. However, only fifty farmers in the intervention used the hermetic bag, limiting the statistical power of the study to draw conclusions about the bags' effectiveness.

An earlier study by Turner et al. (2005) also tested the impact of a package of improved post-harvest technologies (training and inputs: mats, natural-fiber bags, wooden pallets, and insecticide) on groundnut aflatoxin levels and on the level of blood aflatoxin-albumin concentration among adults in Guinea. The study reported that five months after harvest the mean aflatoxin-albumin concentration in the ten treatment villages was 50% of that in the ten control villages, but it is not clear whether treatment villages were selected randomly, limiting the ability to draw causal conclusions from the evidence. Hoffmann and Jones (2018) study post-harvest practices for maize in Kenya but focus on the *adoption* of new technologies (plastic tarps and a mobile flatbed dryer) and do not measure aflatoxin levels.

The present article adds to the sparse literature on interventions to reduce aflatoxins in developing countries. A novel feature of our study is that we evaluate the impact of both drying and storage technologies on reducing aflatoxins, and we partially tease out the effect of individual technologies. In addition, we are the first to identify and offer a low-cost moisture detection device to farmers and to evaluate its effectiveness in reducing aflatoxins. Our results provide practical guidance for policy makers, donors, and practitioners on ways to lower aflatoxins for populations that mainly grow maize for home consumption.

We also contribute to the literature that measures the extent to which knowledge and technology constraints affect household well-being in the developing world. Numerous studies have measured how learning by doing and learning from others affect agricultural technology adoption (Foster and Rosenzweig 1995; Bandiera and Rasul 2006; Conley and Udry 2010). Other studies measured the return to agricultural extension (see Anderson and Feder [2004] for a review), and several recent RCTs measured the impact of extension specifically on adoption of agricultural technologies (Kondylis, Mueller, and Zhu 2017; Ambler, de Brauw, and Godlonton 2018; BenYishay and Mobarak 2018).

The impacts of agricultural technology adoption have been the focus of a large literature (see Foster and Rosenzweig (2010) for a review), and several recent studies have used experimental methods to measure the impact of agricultural technology. These include Duflo, Kremer, and Robinson (2008) who measured returns to inorganic fertilizer among smallholders in Kenya; Lybbert et al. (2018) who measured returns to laser land-leveling technology among Indian rice farmers; and Omotilewa et al. (2018) who measured the impact of hermetic storage bags among Ugandan smallholder maize farmers. The present study adds to this previous work by using an RCT to estimate how access to different drying and storage technologies through a large-scale extension demonstration impacts aflatoxin levels in stored maize. This has important economic and health implications for rural smallholder households.

Our results indicate that the provision of a hermetic storage bag caused a meaningful reduction in total aflatoxin levels in stored maize. On average, households assigned to receiving all inputs were 9% points less likely to have maize samples with total aflatoxin levels above 10 parts per billion (ppb; the European Union limit for maize destined for human consumption), a 33% drop from the control group average. These households were also 11% points less likely to have maize samples with total aflatoxin levels above 20 ppb (the United States limit), a 38% drop from the control group average. Tests of the marginal impact of each input indicate that the hermetic storage bag was the input that led to these decreases. On their own, training, hygrometers, and tarps did not have a statistically significant impact on aflatoxin levels. The lack of impact of tarp provision appeared despite a reduction in the number of households drying maize directly on the bare soil. The lack of impact of providing hygrometers could be due to dry weather conditions in our field site, which may have helped dry maize promptly after harvest.

The positive impact of hermetic bags is particularly significant from a policy perspective. These bags yield other benefits for stored crops beyond aflatoxins reduction, such as reducing quantity and value losses due to insects, rats, and other pests that attack during storage, increasing their value to smallholders (Ng'ang'a et al. 2016a; Omotilewa et al. 2018).

Background

Maize is a main staple crop and the most widely consumed cereal crop produced in SSA, making up a significant portion of calories consumed by millions of low-income smallholder farm households (Shiferaw et al. 2011). As such, the occurrence of acute aflatoxicosis, a lethal disease caused by consumption of food contaminated with high levels of aflatoxins, has only been reported from maize consumption, which may reflect higher daily intakes of maize as compared to groundnuts (Wild and Gong 2010). *Aspergillus flavus*, the fungus primarily responsible for producing aflatoxins, infects maize ears in the field pre-harvest when farmers do not use products intended to control aflatoxins (e.g., Aflasafe®) and/or post-harvest because of poor grain harvest and handling practices (e.g., piling fresh maize on the ground after harvest). In-field contamination from aflatoxins frequently occurs when the plants are stressed by hot and dry conditions. Fungi of the *Aspergillus* genus appear as an olive-green mold on highly infected maize kernels (Woloshuk and Wise 2011), but maize kernels with no visible mold can also contain total aflatoxin levels above those recommended for human consumption.

In the post-harvest period, *A. flavus* comes in contact with maize via contaminated surfaces, such as the soil when maize is dried directly on the ground. Spreading maize on the ground and raking it to turn it or collect it also create micro-abrasions to the pericarp that help *A. flavus* penetrate into kernels. Drying directly on the ground is not uncommon but is done by a minority of farmers. At baseline, about 25% of households dried some or all their maize directly on the ground. Most farmers are able to use alternatives, including drying on raised platforms, roofs, road side, or sometimes in tree branches (with cobs tied together over a branch by the retracted husk).

Contrary to in-field contamination, spread of *A. flavus* during storage is more likely when maize moisture content is higher than 13.5% and conditions are warm and humid (Walker et al. 2018). Drying quickly and thoroughly is a key step in controlling aflatoxins in stored crops (Oyebanji and Efiuvwevwere 1999). Hygrometers, which differ from traditional moisture meters in that they measure air moisture rather than grain moisture directly, may help households know whether and when to put their maize into storage. They have the potential to help farmers solve the problems of the unobservability of grain moisture content and the lack of accessible tools to measure moisture content. Prieto et al. (2021) show that farmers in the same region of Senegal value drier maize but do not trust their ability to detect moisture content using traditional methods (such as touching or biting kernels) and would benefit from a low-cost, reliable tool to measure it. Hygrometers have been shown under laboratory conditions to be reliable moisture detection devices following a simple protocol described below (Tubbs, Woloshuk, and Ileleji 2017). Hygrometers are also much cheaper than traditional moisture meters, at roughly $2.00-$3.00 for the former compared to more than $100 for the latter. However, hygrometers have never been tested for adoption by farmers on a large scale.

Controlling for moisture is necessary but not sufficient, as insects also spread fungi during movement, feeding, defecation, and by boring into kernels (Diener et al. 1987). Hermetic grain storage devices, such as metallic silos and plastic containers, exist but are often priced out of range of smallholder farmers in developing countries. Hermetic bags, while less durable, could be a highly effective, low-cost solution to the hermetic storage problem. Hermetic storage bags are potentially a key tool to controlling aflatoxins contamination due to their ability to block insect infestation in stored grain. By sealing their content, hermetic storage bags limit oxygen, increase carbon dioxide, and kill any insects on the grain at the time of storage (Ng'ang'a et al. 2016b). Maize stored hermetically has been found to have five to eight times lower total aflatoxin levels after 35 weeks than maize stored in polypropylene or jute bags (Ng'ang'a, et al. 2016a). The study concluded that "profuse insect activity probably explain[s] the increase in [aflatoxins] on maize stored in polypropylene and jute bags even when moisture content was within the limit for safe storage" (Ng'ang'a et al. 2016a). These two studies by Ng'ang'a et al., however, were conducted in a laboratory setting; other than the recent Pretari, Hoffmann, and Tian (2019) study, no evidence exists of hermetic storage bags' effect on aflatoxins levels when used in a real-world setting by smallholder farmers. In particular, the bags must be closed and tied in a simple but specific way to provide a hermetic seal; the closing process is at the heart of the training that must accompany the introduction of the bags (in villages assigned to group 5 in our study, it was added to the standard training). It is not clear whether smallholder farmers retain that information and properly close the bags after the training.

The European Union (EU) and United States (US) have strict and enforced regulatory limits on aflatoxins based on the product and its intended use. In the US, the most stringent limit is 20 ppb for maize intended for human consumption and certain types of animal feed (U.S. Food and Drug Administration 2005). The limit in the EU is 10 ppb for maize "to be subjected to sorting or other physical treatment before human consumption" (European Commission 2006).[1] At the time of this study (2016), Senegal had no regulatory limit on total aflatoxin levels in food or animal feed. The Ministry of Agriculture and Rural Development has since committed funding for the development and implementation of a National Aflatoxin Control Plan, focusing on maize and groundnut (Kébé 2017). In countries such as Senegal, with no enforced limit on aflatoxins, households are unlikely to be aware of the hazards posed by aflatoxins (Hell et al. 2000; James et al. 2007). Previous studies that examined total aflatoxin concentrations in Senegal found their levels dependent on agro-ecological zone, variety, shelling

[1]COMMISSION REGULATION (EC) No 1881/2006 sets the limit for maize destined for human consumption to 5 ppb (5 μg/kg) for aflatoxin B1, and to 10 ppb for the sum of aflatoxins B1, B2, G1 and G2. COMMISSION REGULATION (EU) No 165/2010 later reduced the limit to 2 ppb (B1) and 4 ppb (total) for all cereals except maize. The Afla-V AQUA Strip Tests used in this study detect and measure total aflatoxin levels, so we use the 10 ppb limit.

practice, and storage location (Diedhiou et al. 2011). In the area of Southern Senegal where we implement the study described in this article, a recent study found that 17 of 84 maize samples (20%) taken randomly from post-harvest cobs or shelled corn contained positive levels of aflatoxin (Shrestha 2017). In addition, a study by Diedhiou et al. (2011) conducted in the same area of Senegal found that 45% of the aflatoxin strains found in maize samples were toxigenic. Both of these studies suggest high baseline levels of aflatoxin in our study area, justifying the need for intervention.

Intervention

An assessment of post-harvest challenges for maize growers in southern Senegal conducted in 2015, the year prior to our intervention, suggested that maize drying practices of many households in southern Senegal increased the risk of contamination from aflatoxins (Shrestha 2017). The authors observed many farmers drying cobs (without husks) on the bare ground, and many postharvest samples were dirty, with abrasion wounds on the kernels.

Based on this assessment and known ways in which maize gets contaminated with aflatoxins, described above, we focused our intervention on four possible sources of contamination and accumulation of aflatoxins: (*a*) low awareness of aflatoxins, their negative health consequences, and how to prevent contamination; (*b*) absence of tools to sufficiently dry of maize before storage, causing the crop to be stored wet and allowing aflatoxins to accumulate over time; (*c*) lack of tools to avoid maize kernels coming into contact with the bare soil by drying on the ground, which may cause initial contamination from aflatoxins; and (*d*) absence of storage solution that maintains a low moisture level to stop aflatoxins growth and avoids insect infestation during storage, which allows insects to damage maize kernels and move aflatoxins around in the stored product. We provided treated households with four inputs that have the potential to reduce each of these sources of aflatoxins (training, a hygrometer, a tarp, and a hermetic storage bag), which we discuss in detail. Our survey tools and study design were reviewed by the Purdue University Institutional Review Board (IRB) and ruled exempt from IRB review. Enumerators obtained informed consent prior to commencement of each survey.

Training

We provided training on improved post-harvest practices to all treated groups (groups 2, 3, 4 and 5; 1,599 households). Both male and female adults from households selected for the baseline survey were personally invited to the training, but the session was open to everyone in the village. In total, about 3,800 men, women, and youth (estimated to be younger than 15 years) attended. Local extension agents from the Agence Nationale de Conseil Agricole et Rural (ANCAR), Senegal's national agricultural extension agency, conducted the training in their assigned areas. This helped ensure that the people conducting the training understood local challenges, knew the population and were well respected by village leaders. In the study area, maize is generally harvested by cutting the stalks and is then left in the field to begin drying (while other crops are harvested). A primary focus of the training was to describe the existence, sources, evidence, and effects of aflatoxins. To help smallholder address the risk, the training instructed households not to pile maize but to stook stalks after harvest (stacking the stalks in an upright pile off of the ground to allow airflow for drying), even with the husks still covering the ears. Doing so can reduce fungal contamination by preventing kernels from touching the soil and helps avoid ears near the bottom of a pile getting too wet. Finally, the training emphasized the needs to dry maize quickly and off the ground, and to put maize in storage off the bare ground after harvest to stop the accumulation of any aflatoxins in it from the field.

Hygrometers

We provided hygrometers to groups 3, 4, and 5 (1,209 households) as a low-cost grain moisture verification tool. Hygrometers were the smallest and cheapest item we provided; thus, we chose it as the physical input provided to the largest number of treatment groups. In developed countries, farmers and traders use moisture meters to measure grain moisture, but their high price (more than $100) is prohibitive for smallholder farmers in developing countries. Considering this cost barrier, no one in our sample owned or used a moisture meter of any kind prior to our intervention. The hygrometers we distributed were purchased in bulk at a unitary cost of about \$1.13 (imported into the US from China). As a point of comparison, at baseline, 87% of study participants stated that they were willing to pay \$1.79 for a hygrometer that could measure maize moisture content. Hygrometers measure relative humidity and not grain moisture content. However, when grain is placed in a sealed container (such as a small Ziploc bag; see online appendix A) with the hygrometer, the grain's moisture comes into equilibrium with the air in the bag. After 15 minutes, the bag reaches an equilibrium relative humidity, which is read by the hygrometer. Equilibrium relative humidity and temperature (also indicated by the hygrometers we distributed) can be used to calculate the moisture content of the grain in the bag. For ambient temperatures of 21 degrees Celsius and higher, an equilibrium relative humidity of 65% or below corresponds to a grain moisture content of 13.5% or below, which is acceptable for storage (Tubbs, Woloshuk, and Ileleji 2017). Hence, households can simply and reliably know that their grain is dry enough for storage by whether the hygrometer's relative humidity reading is below 65%.

Tarps

Groups 4 and 5 (812 households) received a 10m^2 tarp as an alternative to drying their maize directly on the bare ground. Maize can be spread out on these tarps and the ambient air from the sun used to dry the kernels. Tarps of this size can be used to dry about 200 kg of maize to below 13.5% moisture content over two to three days, depending on the maize's initial moisture content and ambient weather conditions. At baseline, households harvested 675 kg of maize on average, thus most households would dry their entire maize harvest in three to four batches. About 25% of households dried some or all their maize directly on the soil at baseline. All other households dried their maize off the ground, for example in the field (with the husks still on the cobs to prevent contact with the bare soil) or on a wooden or cement platform. The tarps, purchased locally in bulk, cost \$3.27 per 10 m^2 tarp. This cost compares favorably with most households' stated willingness to pay: at baseline, 90% of all households stated that they were willing to pay \$5.36 for a 10 m^2 tarp to dry their maize.

Hermetic Storage Bags

We provided one 50-kg PICS bag to each household in group 5 (404 households) as a hermetic storage bag. Although the PICS bags were less expensive than the tarps, tarps could be purchased locally and were less bulky, thus we provided the PICS bags to the fewest number of treated households. PICS bags hermetically seal grains stored in them and control aflatoxins in two ways. First, they kill any insects on the grain at the time of storage by limiting the amount of oxygen in the bags (Murdock et al. 2012). Lack of oxygen causes insects to go dormant and suffocate, eliminating their movement and ability to spread the fungi that produce aflatoxins. Second, properly closed PICS bags keep grain moisture constant over time, so that any fungi present are less likely to grow on grain that is properly dried before being sealed in the bag (Walker et al. 2018). Hermetic storage bags also eliminate the need for storage pesticides, thus mitigating any health concerns about consuming insecticide-treated maize. A supplier in Dakar stocked PICS bags imported from Nigeria. When purchased in bulk, the 50-kg bags cost \$2.22 each. At the time of intervention, PICS bags were not available locally in Southern Senegal, and no one in our sample was using them prior to the intervention.

Sample and Data

Households included in the study live in the department of Vélingara, region of Kolda, in southern Senegal. The area provides only one maize growing season (May–June to October–November). A census list of villages was provided by our local implementing partner, the Institut Sénégalais de Recherches Agricoles (ISRA). We eliminated areas that were too urban to have a satisfactory number of maize producers or that were too unsafe for field teams to operate. We then randomly selected 200 of the remaining 307 villages to constitute the sample. Power calculations indicated that a sample of 2,000 households in 200 villages, with randomization at the village level, would allow us to detect a 9.3 percentage points drop in the percent of samples with total aflatoxin levels below 10 ppb with 80% power at a 5% level of statistical significance. This corresponds to a Cohen's *h* of 0.2 and is considered a small effect size (Cohen 1988). Calculations were based on one post-intervention measurement (we only measured total aflatoxin levels once), a cluster size of 10 households per village, and used data collected in the same area where this project was implemented and used in Shrestha (2017): 35% of maize samples with aflatoxin levels larger than 10 ppb and an intracluster correlation coefficient of 0.083.

We conducted a rapid census of households in these 200 villages and randomly selected ten households within each village to be included in the study. If a village had fewer than ten households, enumerators randomly selected additional households from the nearest village that had not already been selected to take part in our baseline survey (hence the total number of 209 villages in the analysis sample). In all, 1,981 households were included in the baseline survey, conducted in May 2016 (online appendix B). We collected data from one male respondent and one female respondent within each household. The baseline survey did not include the collection of maize sample and measures of total aflatoxin levels before the intervention.

After concluding the baseline survey, we randomly assigned villages to treatment groups, stratifying by the extension agents that would conduct the trainings to avoid trainer-specific effects that could influence results through the effectiveness of the training. To test the balance of randomization, we ran a multinomial logit model including the baseline variables shown in table 1 (McKenzie 2015). The chi-squared test rejected the null hypothesis that all regressors are jointly equal to zero ($chi^2 = 120.04$; $p = 0.006$; online appendix C). The randomization assigned villages to control and treatment groups, which may allow for some differences in household characteristics across the groups. At baseline in May 2016, households in groups 2 and 4 were more likely than households in the control group (group 1) to have maize in storage from the 2015 harvest ($p < 0.05$). Households in group 5 may have also been more likely than control households to have maize in storage from the 2015 harvest, and households in group 4 may have been less likely to dry maize on the ground after the 2015 harvest, but these coefficients are only statistically significant at the 10% level. As a result, we present all regression results with and without controlling for these two variables (having maize from the 2015 harvest in storage and having dried any maize on the ground after the 2015 harvest); our treatment effects estimates are robust across specifications.

The intervention was implemented in early October 2016, just prior to the 2016 maize harvest. It was followed by two post-intervention surveys. The first post-intervention survey took place in January/February 2017, and reached all households surveyed in the baseline. This survey focused on (*a*) determining who implemented recommended practices from the training, and (*b*) measuring the moisture content of participants' stored maize. Because rains stopped too early to allow full maize maturity in 2016, only 1,495 households harvested maize.

The second post-intervention survey was conducted in May 2017 to measure total aflatoxin levels in maize after three to four months of storage. The maize harvest takes place in October/November of each year. Maize is left to dry for two to three months after that, while the household deals with other crops and put maize into storage around February. The second post-intervention survey only targeted those 1,495 households who reported having maize in storage in the first post-intervention survey in January/February 2017. However, by May 2017, the time of the second post-intervention survey, only 896 households still had maize in storage (from the 2016 harvest). From these, we took 1,580 maize samples (online appendix B). We discuss how we dealt with the analytical challenge arising from the non-random loss of observations due to households not having grain in storage for testing of aflatoxins in the following sections.

We instructed enumerators to take two handfuls of maize per household and note how the household dried and stored the maize in each sample. Most samples were dried only one way and stored in only one type of container. Only 8% of maize samples were dried using more than one method (up to three, for example on a raised platform, in the field, or on the side of road). Only 2% of samples had been stored in multiple containers since harvest; for example, in a traditional granary, in a metallic silo, on the ground in the house. If the household stored maize in more than one type of container, enumerators were instructed to collect samples that used different drying and storage methods within a household. If the household only had maize in one vessel, the instructions were to take

Table 1. Descriptive Statistics at Baseline

	Mean in group					Overall mean	Overall standard deviation
	1	2	3	4	5		
Panel A. Household characteristics							
Household size	12.2	12.6	12.5	11.8	12.3	12.3	6.7
Age of household head (years)	46	47	47	48	48	47	12
Household head had any formal education (%)	35	35	32	30	30	32	47
Woman access mobile phone (%)	67	71	70	70	69	69	46
Distance from village to nearest paved road (km)	12	15	13	15	13	14	16
Panel B. Crop production and storage							
Maize farming experience of household head (years)	19	20	20	20	21	20	12
Area cultivated in 2015 (ha)	4.1	4.2	5.3	4.3	4.2	4.4	12.8
Area of maize cultivated in 2015 (ha)	1.8	1.5	1.4	2.2	1.7	1.7	6.0
2015 maize harvest (kg shelled)	643	732	615	723	660	675	904
Weeks that 2015 maize stored for consumption lasted	13	13	13	15	14	14	13
Still had 2015 maize in storage in May 2016 (%)	57	65	64	68	67	64	48
2015 harvest duration (days)	9.6	9.1	9.5	10.1	10.2	9.7	9.9
Respondent knew that aflatoxins are toxic (%)	25	28	30	31	28	28	45
Dried some maize directly on the ground (%)	25	29	29	19	24	25	43
Stored some maize in a single layer plastic bag (%)	44	40	45	41	46	43	50

Note: N = 1,981 households. Group 1 is the control group, which received no input. Group 2 received training only. Group 3 received training and a hygrometer. Group 4 received training, a hygrometer, and a plastic tarp. Group 5 received training, a hygrometer, a plastic tarp, and a hermetic storage bag. Online appendix C shows the results of statistical tests of randomization balance across all five groups from a multinomial logistic regression. Questions in the baseline survey (May 2016) about maize harvested pertained to the previous harvest (October/November 2015). One household did not report how it dried maize in the baseline, so the number of observations for the variable indicating drying directly on the ground is 1,980.

one sample close to the top of the vessel and the other sample as close to the bottom of the vessel as possible. The instructions to sample maize from different areas stems from the fact that aflatoxin contamination can be local, particularly when low levels of aflatoxins are present.

If the household received a hermetic bag, one of the samples was to be taken in that bag and one from another vessel. Each of the respective samples were placed in a small plastic bag and analyzed separately. The testing equipment was cleaned between each test. Although we intended to take two samples per household from the 896 households that still had maize in the second post-intervention survey, enumerators took only one sample from households with only a very small amount of maize still in storage (212 households). Maize samples were ground by hand and tested using VICAM Afla-V AQUA kits and a VICAM Vertu™ lateral flow reader.

In our data, the correlation in aflatoxin levels between two samples taken from the same household (all groups) was 0.478, so taking two samples with this procedure increased the reliability of our aflatoxin measurement. This correlation coefficient is high in many settings, although in our context it suggests that each sample provides unique information. In our results, we show two analyses that suggest that including data from both samples does not bias our results.

First, we show in online appendix D coefficients from regressions of the household-mean aflatoxin levels (in ppb); each regression include one observation per household.

Results are consistent with our main estimates but suggest a lower impact of providing all inputs (−9.1 ppb on average, vs. −11.5 ppb in the main estimates). The p-values are consistent across models, which should alleviate concerns about downward bias in the standard errors from having more than one sample per household.

Second, we show in appendix E that our results are robust to analyzing only one randomly selected sample per household. Appendix E presents the kernel density of coefficients from 1,000 regressions in which one of the two maize samples was randomly selected (for households in which we took only one sample, that observation is included in each regression). We randomly redrew one of the two samples for each regression. In all graphs, the coefficient estimates of the impact of being assigned to group 5 are always negative. None of the estimates for the other three treatment groups are always negative.

Table 1 describes our sample at baseline, in aggregate and by treatment group. Households were large, with over twelve members on average.[2] Household heads were men (only 0.5% of households in our sample were headed by a woman) in their late forties, about one-third of whom had any formal education (excluding Koranic school). The average distance from the village center to a paved road was 14 km. Household heads had, on average, twenty years of maize farming experience. In this region of Senegal, crops are harvested in October–November of each year. As a result, questions in the baseline survey in May 2016 about maize harvested pertained to the 2015 harvest. On average, households planted 4.4 hectares of all crops in the 2015 season, 1.7 of which were planted with maize (medians: 3 and 1 ha, respectively). The average maize harvest that year was 675 kg (median: 400 kg). Maize was overwhelmingly a self-consumed crop (only 6% of households sold any portion of their harvest; not shown in table 1). Most households were not maize self-sufficient: from the time of storage, they estimated their stored maize would last only 14 weeks on average (median: 11 weeks) before running out. Yet 64% of households still had maize in storage in May 2016 from the 2015 harvest. Households likely consider the "time of storage" as January/February, although they harvest in October/November. As mentioned earlier, households frequently leave maize to field dry for two to three months while harvesting other crops, before bringing it to the household compound for longer term storage.

Knowledge of aflatoxins and post-harvest practices that reduce the risk of contamination was low. At baseline, only 28% of households knew that aflatoxins were toxic. In addition, about 25% of households dried their maize directly on the ground, a key practice that is thought to lead to contamination from aflatoxins. Forty-three percentage of households stored maize in a single layer plastic bag at baseline, which increases the risk of contamination from aflatoxins by insects and by allowing grain moisture to increase over time.

Empirical Model

Our empirical analysis estimates the intent-to-treat effect of being assigned to each treatment group (groups 1–5) on the average level of aflatoxins in stored maize for household *i* in village *j*. We use the following cross-sectional regression modeling aflatoxin levels in the second post-intervention survey as a function of the group assignment:

$$A_{ij} = \beta_1 + \beta_2 Group2_{ij} + \beta_3 Group3_{ij} + \beta_4 Group4_{ij} + \beta_5 Group5_{ij} + \boldsymbol{\delta X_{ij}} + \boldsymbol{\lambda E_j} + \varepsilon_{ij}, \quad (1)$$

where A is a binary variable equal to one if the total aflatoxin level in stored maize was above the threshold for safe human consumption. We show results for the threshold used in the European Union (10 ppb) and the threshold used in the United States (20 ppb). The variables *Group2, Group3, Group4,* and *Group5* are binary variables equal to one if the household was assigned to each group. *Group 2* received the training only. *Group 3* received the training and a hygrometer. *Group 4* received the training, a hygrometer, and a tarp. *Group 5* received the training, a hygrometer, a tarp, and a hermetic storage bag. We also show at the bottom of our main table the

[2]The variable measuring household size is winsorized at the 95th percentile (28 members); in the raw data, 3% of households reported having more than 30 members, up to a maximum of 102 members. Even though some households practice polygamy, the raw figures are unlikely to be accurate.

marginal impact of each input, calculated by subtracting regression coefficients, and if the statistical significance of these estimates (i.e. if the respective marginal impact equals zero) using F-tests.

The vector of the two covariates that were not balanced at baseline is denoted by $\boldsymbol{X_{ij}}$; we present all results excluding and including the variables in this vector, and $\boldsymbol{\delta}$ is the vector of parameters to estimate. In addition, $\boldsymbol{E_j}$ is a vector of six binary variables controlling for the seven extension agents who conducted the training and distributed inputs in village *j*. It is included because, as noted above, the randomization was stratified by extension agent, and λ is a corresponding parameter vector. The error term is denoted by ε_{ij}. Standard errors are clustered by village, reflecting the level of randomization (Glennerster and Takavarasha 2013).

One important feature of our setting is that we can only measure and analyze total aflatoxin levels in maize samples from households who had maize in storage in May 2017, six to seven months after harvest and three to four months after being placed into storage. As mentioned earlier, only 896 of the 1,981 households included at baseline still had maize in storage in May 2017 (1,495 harvested any maize in 2016). The inputs that we provided could influence whether and how much households had in storage at the time of sampling in several ways. The most direct is that providing a hermetic storage bag could reduce mold growth and insect damage on stored grain, and lead to lower losses (Walker et al. 2018). Hygrometers and tarps may also help maintain grain quality, and limit fungal growth, which both lead to post-harvest losses.

This feature could affect our estimates if the treatment assignment affects the probability that households still had maize in storage in May 2017. The dependent variable therefore exhibits the properties of incidental truncation (Greene 2012), analogous to missing wages for people who do not participate in the labor force (Heckman 1979). Indeed, table 2 shows that the likelihood to have maize in storage in May 2017 was about ten percentage points higher in groups 4 and 5 than in the control group ($0.033 \leq p \leq 0.055$). It did not differ statistically significantly between the control group and groups 2 and 3 ($0.124 \leq p \leq 0.287$). To alleviate these concerns, we implement a Heckman selection model, instrumenting for the amount of maize in storage in May 2017 with the amount of maize harvested in 2015 (Heckman 1979). We use the 2015 harvest amount as an instrument because yields are correlated with aflatoxins so the amount harvested in 2016 is not a proper instrument. The table in Appendix F shows the results of both stages of the Heckman selection model. The inverse Mills ratio in all regressions was not statistically significant ($0.180 \leq p \leq 0.186$) and the estimated impacts of the group assignment were similar to our main estimates (described below), suggesting that our results are not biased by the availability of maize in storage to sample for aflatoxins testing.

Results

Table 3 shows our main results, estimated using equation 1. Regression estimates show that only receiving a hermetic bag caused a statistically significant marginal impact on the likelihood that maize stored maize was safe to eat. Being assigned to group 5, which received all inputs, reduced the likelihood that total aflatoxin levels in stored maize were above safety thresholds by about eleven percentage points more than the control group, on average ($0.004 \leq p \leq 0.027$). This impact is meaningful, representing a 33% (38%) drop from the control group average.

Comparisons of coefficients for groups 2 to 5 suggest that the hermetic storage bags were the key input that led to the drop in total aflatoxin levels: as displayed in the last row of table 3, the hermetic bags themselves were responsible for a nine-percentage point decrease in the likelihood that total aflatoxin levels were above the EU and US safety thresholds ($0.014 \leq p \leq 0.052$). This row compares coefficient estimates for group 5, who received all inputs, and group 4, who receive all inputs other than a hermetic bag.

None of the other inputs, whether together or individually, caused any statistically significant decline in aflatoxin levels. Consistent with the lower percentage of samples above the thresholds in groups 2–5 compared to the control group (group 1), the regression estimates of the impact of the training were negative and of meaningful magnitude (five to six percentage points), but they were not statistically significant. The marginal contribution of the hygrometer and tarp, however, were both small in magnitude (between 0.2 and 3% points) and not statistically significant.

Table 2. Determinants of Probability of Still Having Maize in Storage in May 2017

	(1)	(2)	(3)	(4)
Dependent variable	1 if household still has maize in storage in second post-intervention survey; 0 otherwise			
Estimator:	OLS	OLS	Probit	Probit
Group 2 (training only)	0.082	0.059	0.081	0.061
	(0.053)	(0.049)	(0.053)	(0.048)
Group 3 (training+hygrometer)	0.066	0.058	0.065	0.056
	(0.059)	(0.053)	(0.058)	(0.053)
Group 4 (training+hygro+tarp)	0.115**	0.093*	0.114**	0.092*
	(0.054)	(0.048)	(0.054)	(0.048)
Group 5 (training+hygro+tarp +hermetic bag)	0.124**	0.104**	0.124**	0.101*
	(0.058)	(0.052)	(0.057)	(0.052)
Constant	0.335***	0.137*		
	(0.060)	(0.083)		
Observations	1,981	1,980	1,981	1,980
R-squared	0.029	0.098		
Trainer fixed effects included	Yes	Yes	Yes	Yes
Control variables included	No	Yes	No	Yes

Note: Standard errors clustered by village in parentheses. ***p < 0.01, **p < 0.05, *p < 0.10. OLS: ordinary least squares regressions (models are linear probability models). Coefficients in columns 3 and 4 are marginal effects. One household did not report how it dried maize in the baseline survey, so the number of observations in columns 2 and 4 is 1,980. Control variables include household size, age of the household head (in years), whether the household head had any formal education, distance from village center to paved road (in km), maize farming experience of the household head (in years), weeks that stored 2015 maize lasted, whether the household consumes moldy maize, 2015 maize harvest put into storage (in kg shelled), whether the household had 2015 maize harvest still in storage in May 2016, 2015 harvest duration (in days), whether the respondent knew that aflatoxins are toxic, whether the household dried 2015 maize directly on the ground, whether the household stored 2015 maize in a single layer plastic bag, and whether the household stored 2015 maize on the cob.

Additional Analyses

We conduct two additional analyses. First, we estimate the impact of the assignment to a group on the exact total aflatoxin levels, in parts per billion, rather than on binary indicators of samples having levels of aflatoxins above a certain threshold. Before we describe these results, we note that this measure presents one important limitation: our count of total aflatoxin levels is censored at 100 ppb. The machine we used to measure total aflatoxin levels requires a second reading on a different setting to read exact levels over 100 ppb. We opted not to undertake any second reading because (*a*) we did not know when planning the study what level of aflatoxins to expect and how many readings would be above 100 ppb; (*b*) 100 ppb is well above the recommended safe levels of 10 ppb or 20 ppb so the loss of precision was *a priori* acceptable; (*c*) the tests we use lose precision as aflatoxins levels increase so that we would not be able to measure very high levels of aflatoxins, which would effectively censor our measure (albeit at a much higher level); and (*d*) we wanted to contain the cost of aflatoxins testing ($6 per test strip, plus labor and transport costs; a second strip would have been needed for each second reading). As a result, our data cannot differentiate between total aflatoxin levels of 100 ppb and higher levels. Of the 1,580 samples we tested, 134 (8%) returned an "above range" reading. In our measures and analyses of mean total aflatoxin levels, we set all "above range" readings to 100 ppb when running OLS estimation (and to missing when running censored regression).

Regression analyses confirm these trends and the three main results presented above (table 3, columns 5 and 6). First, being assigned to receiving all inputs (group 5) lowered aflatoxin levels by 11.5 ppb, on average, compared to the control group (p = 0.004 in column 5 and p = 0.005 in column 6). The magnitude of this impact is meaningful, representing almost half of the average total aflatoxin level in the control group.

Consistent with our main results, total aflatoxin levels in groups 2, 3, and 4 were not statistically significantly lower than in the control group, suggesting that only the hermetic storage bag decreased aflatoxin levels. This result was confirmed by the analysis of the marginal impact of each input on average levels of aflatoxins, presented in the last three rows of table 3. The marginal impact of the hygrometer over that of the training, and of

Table 3. Intention to Treat (ITT) Impacts of Treatments on Total Aflatoxin Levels in Stored Maize

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	1 if Total aflatoxin level > 10 ppb; 0 if ≤10 ppb		1 if total aflatoxin Level > 20 ppb; 0 if ≤20 ppb		Total aflatoxin level (ppb)	
Food safety standard:	European Union standard		United States standard		-	
Estimator:	LPM		LPM		OLS	
Group 2 (training only)	−0.052	−0.051	−0.061	−0.060	−6.67	−6.64
	(0.048)	(0.048)	(0.049)	(0.049)	(4.18)	(4.18)
Group 3 (training +hygrometer)	−0.039	−0.038	−0.028	−0.026	−5.48	−5.43
	(0.056)	(0.056)	(0.055)	(0.055)	(4.35)	(4.36)
Group 4 (training+hygro +tarp)	−0.020	−0.018	−0.025	−0.024	−3.81	−3.77
	(0.054)	(0.054)	(0.054)	(0.054)	(4.53)	(4.56)
Group 5 (training+hygro +tarp+hermetic bag)	−0.110**	−0.109**	−0.115**	−0.113**	−11.52***	−11.47***
	(0.049)	(0.049)	(0.048)	(0.048)	(3.97)	(4.00)
Constant	0.301***	0.310***	0.267***	0.284***	22.81***	23.25***
	(0.053)	(0.059)	(0.052)	(0.056)	(4.20)	(4.44)
Observations	1,580	1,580	1,580	1,580	1,580	1,580
R-squared	0.026	0.026	0.021	0.022	0.035	0.036
Trainer fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes
Control variables included	No	Yes	No	Yes	No	Yes
Mean of dependent variable in group 1 (control)	0.33		0.29		24.4	
Marginal impact of hygrometer (G3-G2)	0.013	0.013	0.033	0.034	1.19	1.21
Marginal impact of tarp (G4-G3)	0.019	0.020	0.003	0.002	1.67	1.66
Marginal impact of hermetic bag (G5-G4)	−0.090*	−0.091**	−0.090**	−0.089**	−7.71**	−7.70**

Note: Standard errors clustered by village in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1. Regressions in columns 1–4 are linear probability models (LPM). Each observation is one maize sample; we analyze two samples per household from 684 households that still had maize in storage 3–4 months after harvest; 212 other households had a small amount of maize still in storage, from whom we took only one sample. For the 134 samples registering total aflatoxin levels higher than 100 ppb, we top code the value at 100 ppb. The European Union permits a maximum concentration of aflatoxins in maize destined for human consumption of 10 ppb; in the United States the equivalent limit is 20 ppb. At the time of the study, Senegal did not have an official maximum amount of aflatoxins allowed in foods. Group 1 (control) is the omitted group. Control variables include two binary variables indicating whether the household had in storage in May 2016 maize from the 2015 harvest and whether the household dried any part of its 2015 maize harvest on the ground. Marginal impacts of each input are the differences between coefficients for groups 3–5, as indicated in parentheses; p-values are from F-tests.

the tarp over that of the training and hygrometer, were small in magnitude (1.2 to 1.7 ppb) and not statistically significant. The hermetic bag itself, however, led to a 7.7 ppb decrease in total aflatoxin levels over the training, tarp, and hygrometer on average (p = 0.014 and 0.015 in columns 5 and 6).

To address limitations from the definition and distribution of the average aflatoxin levels, described above, we show in online appendix G coefficients from interval regressions modeling the censoring at 100 ppb (columns 1 and 2), and coefficients from regressions using the inverse hyperbolic sine of the total aflatoxin levels because the raw measure has a long right tail (columns 3 and 4). Both sets of results were similar to our main results.

The second additional analysis we undertake shows that the impacts of the four inputs on total aflatoxin levels in stored maize were not heterogeneous across the distribution of aflatoxin levels in our samples. Figure 1 shows the cumulative distribution function of total aflatoxin levels in the maize samples in the control and treatment groups. It suggests that impacts were distributed throughout the sample rather than stemming from a large impact on few households, for example those with very high total aflatoxin levels.

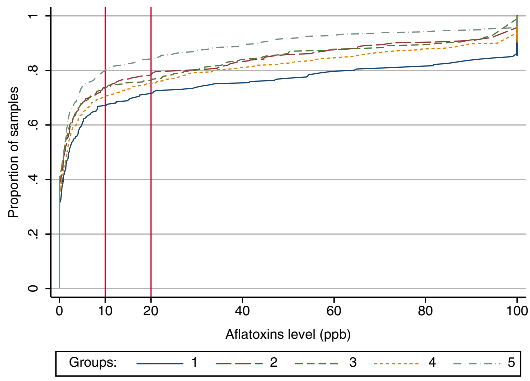

Figure 1. Cumulative distribution functions of Total aflatoxin levels by treatment group.

Note: Group 1 is the control group. Group 2 received training only. Group 3 received training and a hygrometer. Group 4 received training, a hygrometer, and a $10m^2$ tarp. Group 5 received training, a hygrometer, a $10m^2$ tarp, and a hermetic grain storage bag. Total aflatoxin levels are censored at 100 ppb.

Table 4 presents regression-based estimates of heterogeneity in impacts, which concur with the finding that impacts were not heterogeneous. It presents coefficients from linear probability model regressions in which all right-hand side variables of equation 1 were interacted with various dimensions of heterogeneity that may influence the impacts of the inputs: household size, age of the household head, formal education of the household head, household wealth, female access to a mobile phone in the household, and female household member attended the training. None of the interaction coefficients are statistically significant at the 5% level or below.

Pathways to Impacts

In this section we present evidence to understand why each input does or does not lead to changes in total aflatoxin levels. First, despite the lack of evidence that training alone reduced total aflatoxin levels, the training did increase households' awareness of aflatoxins and knowledge of their toxicity. In each survey wave, we asked respondents about their awareness of aflatoxins and their toxicity. The percentage of farmers who were aware of aflatoxins and their toxicity increased by 38–49 percentage points between the baseline and first post-intervention surveys in the groups that received the training (groups 2–5), but decreased by seven percentage points in the control group (results not shown in tables). Note that increased awareness of aflatoxins' harmfulness could have led farmers to sort their maize based on estimated level of contamination and possibly give the worst-looking grains to animals. Further, farmers could have sorted differently based on the other inputs that they received. This behavior would have taken out of the universe of possible maize samples the most contaminated kernels and imply that the impacts that we measured are lower bounds of the potential real impacts. The training's success in transferring information was likely due in part to households having been trained by local extension agents, well known to and trusted by village chiefs and households, and with a medium- to long-term presence in the villages (Jones and Kondylis 2018). The lack of impacts of the training alone suggests that information itself is not sufficient.

Second, the lack of effect of providing a hygrometer on total aflatoxin levels was likely not due to low compliance (use of the hygrometer). In our first post-intervention survey, 43.5% of the households that received a hygrometer reported having used it to test the dryness of their grain (results not shown). To investigate the possible role of noncompliance, we estimated the treatment-on-the-treated (TOT) impacts of actually using the hygrometer. We implemented a two-stage least squares specification in which a self-reported indicator of actually using the hygrometer was instrumented by the treatment assignment, which provides a local average treatment effect of being induced to use the hygrometer by the treatment assignment (Angrist and Pischke 2009). These results, presented in table 5 showed that using the hygrometer did not lead to a statistically significant change in the likelihood that maize samples tested below 10 or 20 ppb on average. We conclude that the lack of impacts of the assignment to receive a hygrometer was not due to low compliance.

The lack of effect of assignment to receive a hygrometer could have reflected the fact that farmers already knew how to take advantage of natural local conditions to dry grains. For example, in January 2017 we tested the moisture content of maize (using modern, precise moisture meters brought from the United States) to assess how dry maize is when it goes into storage. At that time, we found that the moisture content of maize going into storage was not a concern, with 96% of all samples

Table 4. Heterogeneity in Impacts

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	1 if total aflatoxin level > 10 ppb; 0 if ≤10 ppb (European Union standard)					
Variables in main model interacted with:	Household size		Age of household head		Household head has any formal education	
Group 2 * Interaction variable in heading	−0.003	−0.003	0.001	0.001	0.055	0.051
	(0.006)	(0.006)	(0.003)	(0.003)	(0.093)	(0.092)
Group 3 * Interaction variable in heading	0.002	0.002	0.005	0.005	0.058	0.049
	(0.006)	(0.007)	(0.004)	(0.004)	(0.097)	(0.096)
Group 4 * Interaction variable in heading	−0.003	−0.003	0.003	0.003	−0.057	−0.070
	(0.007)	(0.007)	(0.003)	(0.003)	(0.095)	(0.095)
Group 5 * Interaction variable in heading	−0.004	−0.004	0.005	0.005	0.007	−0.001
	(0.006)	(0.006)	(0.003)	(0.003)	(0.093)	(0.091)
Observations	1,580	1,580	1,580	1,580	1,580	1,580
R-squared	0.033	0.034	0.034	0.034	0.034	0.035
Trainer fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes
Control variables included	No	Yes	No	Yes	No	Yes

	(7)	(8)	(9)	(10)	(11)	(12)
Dependent variable:	1 if total aflatoxin level > 10 ppb; 0 if ≤10 ppb (European Union standard)					
Variables in main model interacted with:	Household wealth		Female access to mobile phone in household		Woman attended training	
Group 2 * Interaction variable in heading	0.000002	−0.000029	0.017	0.013	−0.098	−0.097
	(0.000135)	(0.000141)	(0.094)	(0.094)	(0.206)	(0.205)
Group 3 * Interaction variable in heading	0.000162	0.000172	0.129	0.135	−0.039	−0.041
	(0.000115)	(0.000115)	(0.093)	(0.093)	(0.203)	(0.202)
Group 4 * Interaction variable in heading	0.000021	0.000049	0.062	0.075	−0.054	−0.057
	(0.000144)	(0.000146)	(0.095)	(0.093)	(0.204)	(0.202)
Group 5 * Interaction variable in heading	0.000074	0.000096	0.138	0.143*	0.011	0.010
	(0.000136)	(0.000140)	(0.086)	(0.086)	(0.201)	(0.201)
Observations	1,577	1,577	1,580	1,580	1,502	1,502
R-squared	0.035	0.037	0.034	0.036	0.027	0.028
Trainer fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes
Control variables included	No	Yes	No	Yes	No	Yes

Note: Standard errors clustered by village in parentheses. ***p < 0.01, **p < 0.05, *p < 0.10. Regressions are ordinary least squares. The variable indicated in the heading and the four binary variables for the four treatment groups are always included in all regressions but not shown for clarity. Control variables include two binary variables indicating whether the household had in storage in May 2016 maize from the 2015 harvest, and whether the household dried any part of its 2015 maize harvest on the ground, as well as the interaction of each of these with the variable indicated in the table heading. The variable indicated in the heading is interacted with all right-hand side variables, including the trainer fixed effects. The number of observation is lower in columns 5, 6, 11, and 12 due to missing values in the interacted variable.

having a moisture content of 13.5% or below, the threshold under which fungi are unlikely to grow. Thus, it seems likely that receiving a hygrometer did not have a meaningful impact on lowering total aflatoxin levels as maize was likely thoroughly dried when it was stored and thus a moisture reading was not necessary.

Third, the lack of impact of receiving a tarp on total aflatoxin levels runs counter to existing evidence that providing a tarp lowers total aflatoxin levels in stored groundnuts in Ghana (Hoffmann et al. 2018). Our data showed that 41.5% of households reported using the tarps, and that being assigned to receive a tarp led to a 30% point increase in households reporting drying their maize on a sheet or mat ($p < 0.001$), a nearly tenfold increase from the average baseline level (table 6, columns 1 and 2). Yet, being assigned to receive a tarp failed to lower total aflatoxin levels on average. As for hygrometers, noncompliance did not explain the lack of main impacts of the tarp. Regression coefficients from a TOT analysis of the impact of using the tarp on total aflatoxin levels, using a two-stage least squares approach instrumenting use of the tarp by the

Table 5. Treatment-on-the-Treated (TOT) Impacts of the Hygrometer on Total Aflatoxin Levels in Stored Maize

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	1 if total aflatoxin level > 10 ppb; 0 if ≤10 ppb		1 if total aflatoxin Level > 20 ppb; 0 if ≤20 ppb		Total aflatoxin level (ppb)	
Food safety standard:	European Union standard		United States standard		-	
Estimator:	2SLS		2SLS		2SLS	
1 if household used hygrometer	−0.047	−0.044	−0.036	−0.035	−5.45	−5.41
	(0.057)	(0.057)	(0.057)	(0.056)	(4.54)	(4.53)
Constant	0.276***	0.286***	0.236***	0.256***	19.40***	20.06***
	(0.047)	(0.053)	(0.044)	(0.050)	(3.32)	(3.67)
Observations	1,580	1,580	1,580	1,580	1,580	1,580
R-squared	0.021	0.021	0.014	0.015	0.03	0.03
Trainer fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes
Control variables included	No	Yes	No	Yes	No	Yes

Note: Standard errors clustered by village in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1. Each observation is one maize sample; we analyze two samples per household from 684 households that still had maize in storage 3–4 months after harvest; 212 other households had a small amount of maize still in storage, from whom we took only one sample. Group 1 (control) is the omitted group. Results are local average treatment effects, where control variables include two binary variables indicating whether the household had in storage in May 2016 maize from the 2015 harvest, and whether the household dried any part of its 2015 maize harvest on the ground. The indicator of using the hygrometer was instrumented by the random treatment assignment; first stage results are not reported.

treatment assignment, were not statistically significant at the 5% level or lower (table 7).

Also, only about 25% of households reported drying maize directly on the ground at baseline, so it is possible that the change in drying method was not widespread enough to generate a measurable impact on average total aflatoxin levels: although providing tarps led to a large increase in sheet/mat/tarp drying, households have other options to dry off the ground, such as using a roof, a matt, or a concrete slab as a drying surface. As a result, the decrease in drying on the ground following the intervention (14% point, or 56% of baseline average), although large, was less pronounced than the increase in sheet/mat/tarp drying (table 6, columns 3 and 4). It is also possible that the total aflatoxin levels we measured in the second post-intervention survey originated while the maize was in the field rather than during drying and/or storage. If this is true, then the maize we sampled would already have been contaminated with aflatoxins before the inputs such as the tarp could have been used to mitigate them.

Finally, hermetic storage bags limit the spread of aflatoxins when grains are properly dried before being inserted in a bag and when the bags are properly closed (Ng'ang'a et al. 2016a). We can think of two possible reasons why the hermetic bags had a significant marginal impact on aflatoxin reduction of any of the interventions offered to participants. First, as mentioned earlier, the physical properties of bags – they stop airflow and suffocate insects – have been shown under laboratory conditions to stop the spread of aflatoxins in stored grains (Diedhiou et al. 2011; Shiferaw et al. 2011). This also seems to hold true in our smallholder farm household setting in southern Senegal, as maize was stored in the hermetic bags for 3–4 months before we took aflatoxin samples. As such, the hermetic bag's ability to control the spread of aflatoxins over this relatively long time period was a key technological improvement over the status quo, which is storing in one-layer woven bags that let air and moisture into the bags and allow insects to thrive and spread aflatoxins.

Second, there could have also been a behavior response by smallholders to receiving the hermetic bags, as they were a completely new technology to all of the farmers in our sample. During the training, participants where shown the benefits of the hermetic bags and their proper use that yields those benefits. Good harvesting and post-harvest practices are not

Table 6. Determinants of Probability of Drying Maize Directly on the Ground

Dependent variable:	(1)	(2)	(3)	(4)
	1 if household reported drying maize on a sheet or mat in 2016; 0 if not		1 if household reported drying maize directly on the ground in 2016; 0 if not	
Group 2 (training only)	0.056	0.055	−0.050	−0.050
	(0.036)	(0.037)	(0.041)	(0.041)
Group 3 (training+hygrometer)	−0.007	−0.008	−0.050	−0.050
	(0.029)	(0.030)	(0.039)	(0.040)
Group 4 (training+hygrometer+tarp)	0.302***	0.299***	−0.143***	−0.144***
	(0.038)	(0.038)	(0.034)	(0.035)
Group 5 (training+hygrometer+tarp +hermetic bag)	0.333***	0.331***	−0.148***	−0.148***
	(0.046)	(0.046)	(0.036)	(0.036)
Constant	0.126***	0.124***	0.192***	0.194***
	(0.039)	(0.041)	(0.037)	(0.040)
Observations	1,498	1,497	1,498	1,497
R-squared	0.125	0.126	0.037	0.037
Trainer fixed effects included	Yes	Yes	Yes	Yes
Control variables included	No	Yes	No	Yes
Mean of dependent variable at baseline:	0.032		0.252	

Note: Standard errors clustered by village in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.10. Regressions are linear probability models. One household did not report how it dried maize in the baseline survey, so the number of observations in columns 2 and 4 is 1,497. Results are local average treatment effects, where control variables include household size, age of the household head (in years), whether the household head had any formal education, distance from village center to paved road (in km), maize farming experience of the household head (in years), weeks that stored 2015 maize lasted, whether the household consumes moldy maize, 2015 maize harvest put into storage (in kg shelled), whether the household had 2015 maize harvest still in storage in May 2016, 2015 harvest duration (in days), whether the respondent knew that aflatoxins are toxic, whether the household dried 2015 maize directly on the ground, whether the household stored 2015 maize in a single layer plastic bag, and whether the household stored 2015 maize on the cob.

Table 7. Treatment-on-the-Treated (TOT) Impacts of the Tarp on total Aflatoxin Levels in Stored Maize

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	1 if total aflatoxin level > 10 ppb; 0 If ≤10 ppb		1 if total aflatoxin level > 20 ppb; 0 If ≤20 ppb		Total aflatoxin level (ppb)	
Food safety standard:	European Union standard		United States standard		-	
Estimator:	2SLS		2SLS		2SLS	
21 if household used sheet/mat/tarp	−0.144	−0.141	−0.167	−0.167	−14.61*	−14.72*
	(0.114)	(0.114)	(0.108)	(0.108)	(8.03)	(8.05)
Constant	0.297***	0.310***	0.266***	0.287***	21.18***	22.08***
	(0.051)	(0.059)	(0.049)	(0.056)	(3.41)	(3.97)
Observations	1,459	1,459	1,459	1,459	1,459	1,459
Trainer fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes
Control variables included	No	Yes	No	Yes	No	Yes

Note: Standard errors clustered by village in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1. Each observation is one maize sample; we analyze two samples per household from 684 households that still had maize in storage 3–4 months after harvest; 212 other households had a small amount of maize still in storage, from whom we took only one sample. For the 134 samples registering total aflatoxin levels higher than 100 ppb, we top code the value at 100 ppb. The European Union permits a maximum concentration of aflatoxins in maize destined for human consumption of 10 ppb; in the United States the equivalent limit is 20 ppb. At the time of the study, Senegal did not have an official maximum amount of aflatoxins allowed in foods. Group 1 (control) is the omitted group. Results are local average treatment effects, where control variables include two binary variables indicating whether the household had in storage in May 2016 maize from the 2015 harvest and whether the household dried any part of its 2015 maize harvest on the ground. The indicator of using a sheet/mat/tarp was instrumented by the random treatment assignment; first stage results are not reported.

effective over the long term without good storage practices and technologies. It may have been that the hermetic bags were viewed by participants as the key input or technology, which was novel enough and effective enough to motivate them to reduce aflatoxin contamination at the harvesting and drying stages more than farmers in other treatment groups. This argument would not apply to hygrometers and tarps, for which low-cost substitute "technologies" exist. For example, people can use touch or biting kernels to (imperfectly) test dryness instead of a hygrometer (Prieto et al. 2021), and they can use roofs, roadsides, concrete slabs, or mats rather than tarps to dry maize off the ground.

Conclusion

The present article discusses results from an RCT-based study of an intervention aiming to improve post-harvest practices and reduce aflatoxins in maize produced and stored by smallholder farmers in Senegal. To test which constraints are binding to prevent safe maize drying and storage, we provided training (on the dangers of aflatoxins and best practices to prevent them), a low-cost moistur meter called a hygrometer (to reduce maize moisture content levels, thus minimizing accumulation of aflatoxins in stored maize), tarps (to reduce contact with possibly contaminated soil that may contain aflatoxins), and hermetic storage bags (to kill insects which spread aflatoxins in stored maize and to maintain moisture content). We found that, although households did attend trainings and use the hygrometers and tarps, only receipt of a hermetic storage bag caused a statistically significant reduction in average total aflatoxin levels. The impact of receiving a hermetic bag was meaningful, with over-30% drops in the likelihood that maize samples contained total aflatoxin levels above the EU and US food safety limits. Thus, the lack of a safe storage structure for grains was the primary constraint preventing farmers from lowering total aflatoxin levels in their stored maize.

We conducted simple cost-effectiveness calculations of the inputs. The training cost about \$6,100 and reached about 3,800 households. Only 1,599 of these households were part of the study, however, for a unit cost of \$3.81. Hygrometers cost about \$1.13 when purchased in bulk; they were not available locally at the time of the study, but we estimate a local retail price of about \$2.50 (Channa et al. 2018). Tarps were purchased locally, at a price of \$3.27 per 10 m^2 portion. The estimated manufacturing, transport, and local distribution cost of a 50-kg hermetic bag, based on the wholesale cost of PICS bags in Dakar, was \$2.22. Given the average 11.5 ppb decrease in total aflatoxin levels observed for households in group 5, a conservative estimate of the cost-effectiveness of that intervention is therefore \$1.03 per ppb of aflatoxin reduced (\$11.8/11.5 ppb). Considering that hygrometers and tarps did not lower total aflatoxin levels, the cost effectiveness of training and PICS bag provision (PICS bags require a training on their proper use) would be \$0.52 per ppb (\$6.03/11.5 ppb). Both calculations are likely upper bounds, because (*a*) a simpler training that focuses only on how to use the bag would cost less than our more extensive training, (*b*) the costs of PICS bags and training occur one time, but the benefits from reducing aflatoxins can extend into the future if participants re-use the bags and retain the knowledge acquired during training, and (*c*) hermetic bags also provide other benefits, such as insect and rodent control, that are not considered in this simple calculation. Comparing these rates to the cost-effectiveness of other health interventions is challenging, primarily due to the difficulty to translate a one-ppb reduction in total aflatoxin levels in stored maize to health outcomes.

One caveat to the interpretation of our results is that because the inputs were cumulative by treatment groups, the estimates of the marginal impacts of each input are conditional on households having received all other inputs, and results are not robust to re-ordering inputs. For example, even our estimate of the marginal impact of the hermetic bag is conditional on households having received the other three inputs. Our data cannot tell with certainty whether the hermetic bags would have had a significant impact on their own. In particular, the hermetic storage bags require a training about their proper use to be effective. Our evidence of their impact must therefore be understood in the context of our intervention, which provided inputs cumulatively. Testing different combinations of inputs, with an eye toward cost effectiveness, is an important topic for future research.

Our finding that providing plastic tarps to dry maize has no significant effect on total aflatoxin levels differs from that of Hoffmann et al. (2018) and Pretari, Hoffmann, and Tian (2019), the only other studies to separately test the impact of tarp provision on aflatoxins. Hoffmann et al. (2018) tested the effectiveness of tarp use on reducing total aflatoxin levels in groundnuts in Ghana, and Pretari, Hoffmann, and Tian (2019) studied maize in Kenya; further research is needed to establish more precisely the conditions under which tarps are effective at reducing total aflatoxin levels across a variety of crops and geographic locations.

Finally, the finding that hermetic storage bags caused significant marginal decreases in total aflatoxin levels, including for maize stored in other vessels, raises interesting questions about behavioral responses to the intervention. The result suggests that harvesting, drying, and storage practices may go together in the mind of smallholder farm households. Additional evidence is required to understand the direct (e.g., less air flow, lower moisture content, and fewer insects) and indirect (e.g., better post-storage care of grains) impacts of hermetic grain storage (Zheng et al. 2013). Our results suggest that, from a policy and development implementation perspective, post-harvest interventions should consider harvest, post-harvest, and storage issues together rather than separately when engaging with smallholders. This finding also supports the notion that introducing simple new technologies that solve real problems for farmers (in this case post-harvest loss and aflatoxin contamination) can overcome important constraints to improve food safety and health of smallholder farm households.

Supplementary Material

Supplementary material are available at *American Journal of Agricultural Economics* online.

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